Center for Gravitational Wave Astronomy
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Gravitational radiation from black-hole binaries

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In collaboration with:
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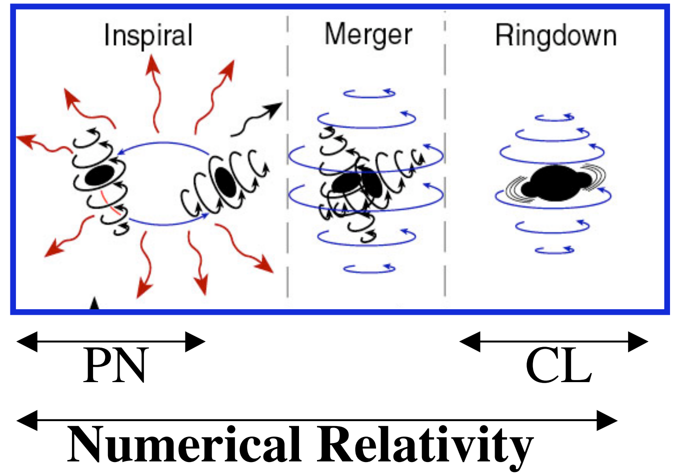
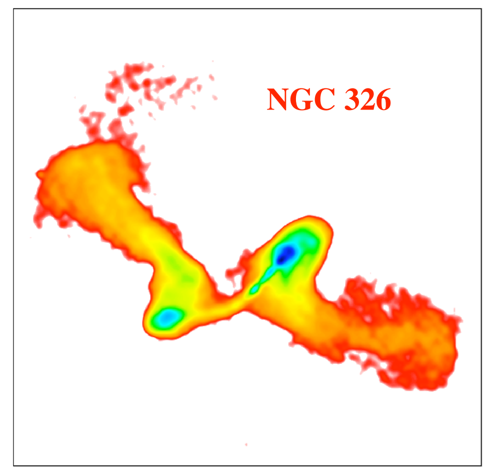
Greenbelt, Maryland

Black hole binary coalescences

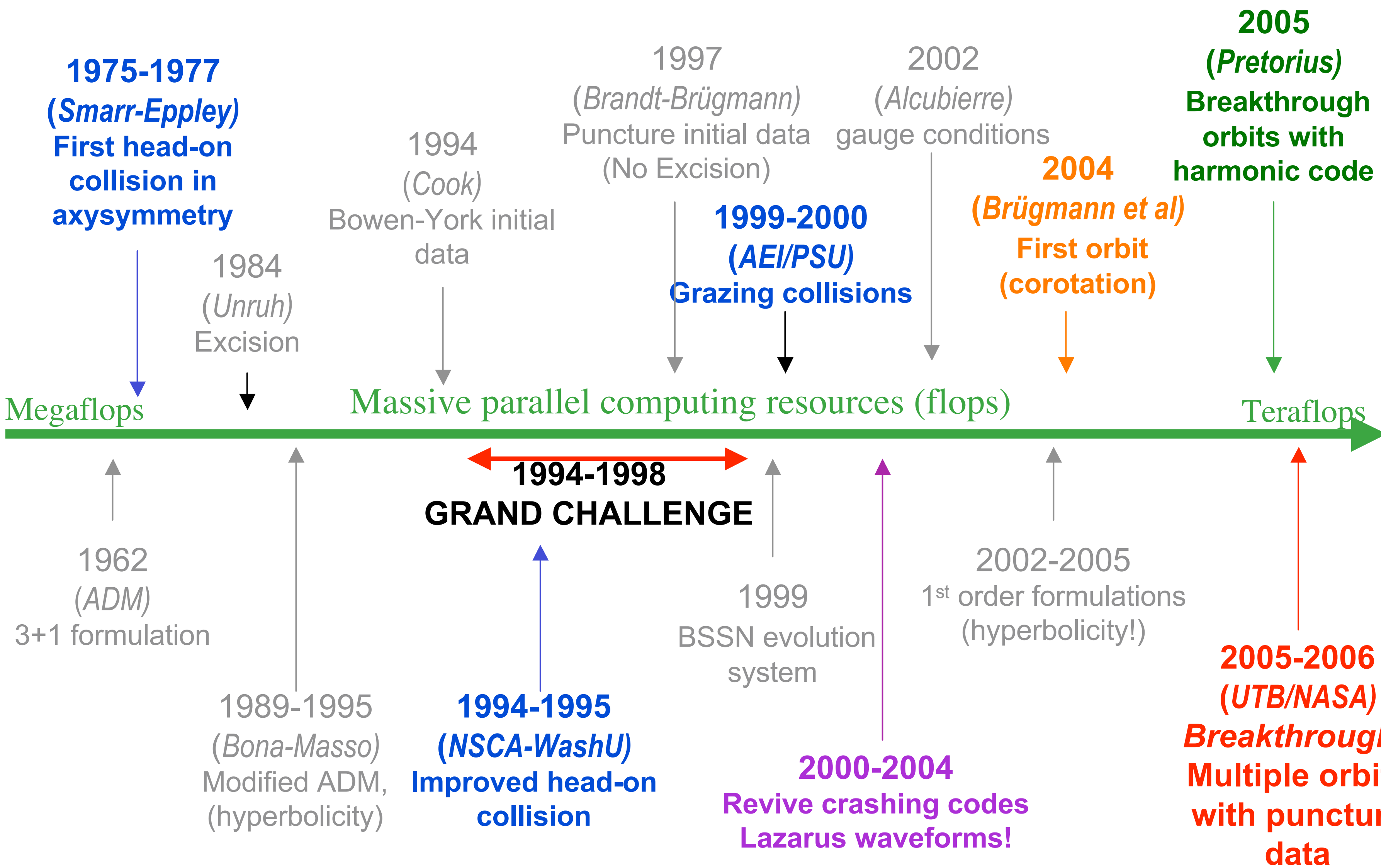
- Binary black holes (BBH) of comparable masses are powerful sources of gravitational waves (GW)
- Accurate BBH models (in all phases) are important:
  - Event detection (before GW are detected)
    - ♣ Important for LIGO (now taking data at design sensitivity), etc
    - ♣ Easier for LISA …
  - Parameter extraction (after GW are detected)
    - ♣ Masses, spins, eccentricity of the orbit, etc
- Understanding/testing strong-field gravity in General Relativity (GR)
- Consequences in astrophysics about the formation history of galaxies
  - Recoil (m1≠m2)
    - ♣ BH ejection rates from clusters and galaxies
  - Spins
    - ♣ Merger population statistics (accretion implies high spin, but mergers at random angles decrease spin)





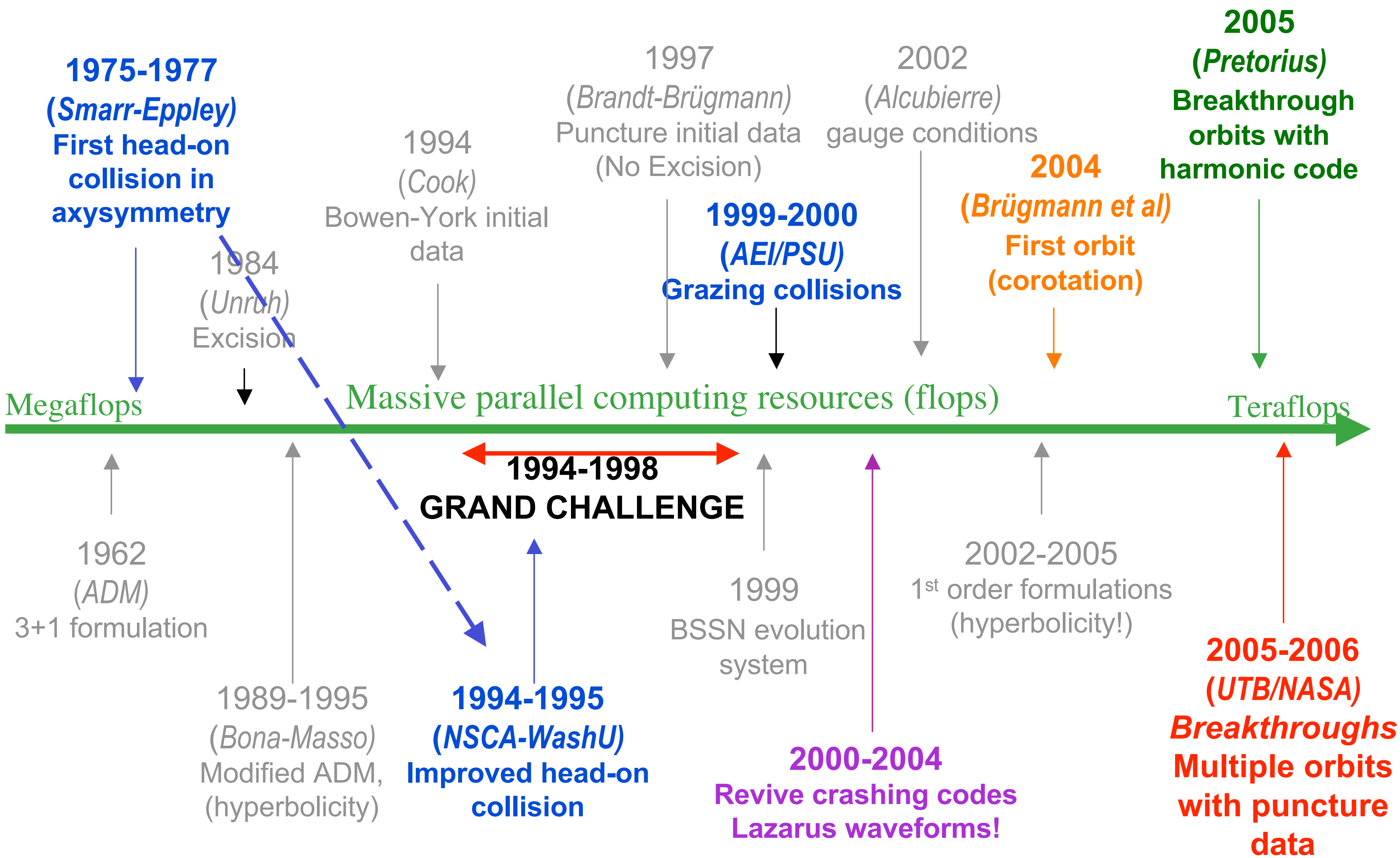
Spin-flip in X-shaped radio morphologies induced by merger?

Numerical Relativity: 30-40 years of challenges



This view is not meant to be complete. See also Alcubierre’s talk, AANR meeting, Guanajuato (MX)

Numerical Relativity: 30-40 years of challenges



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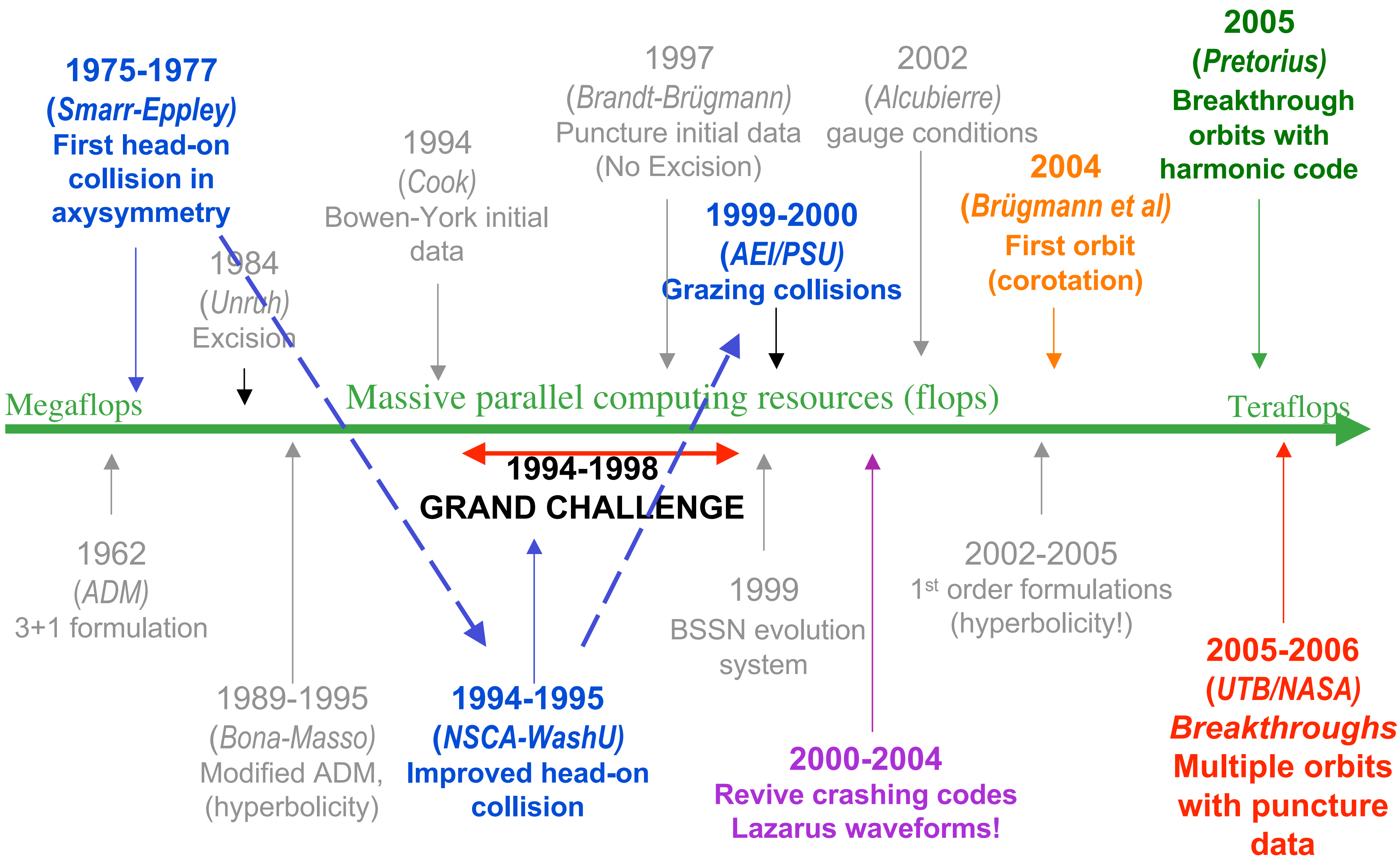

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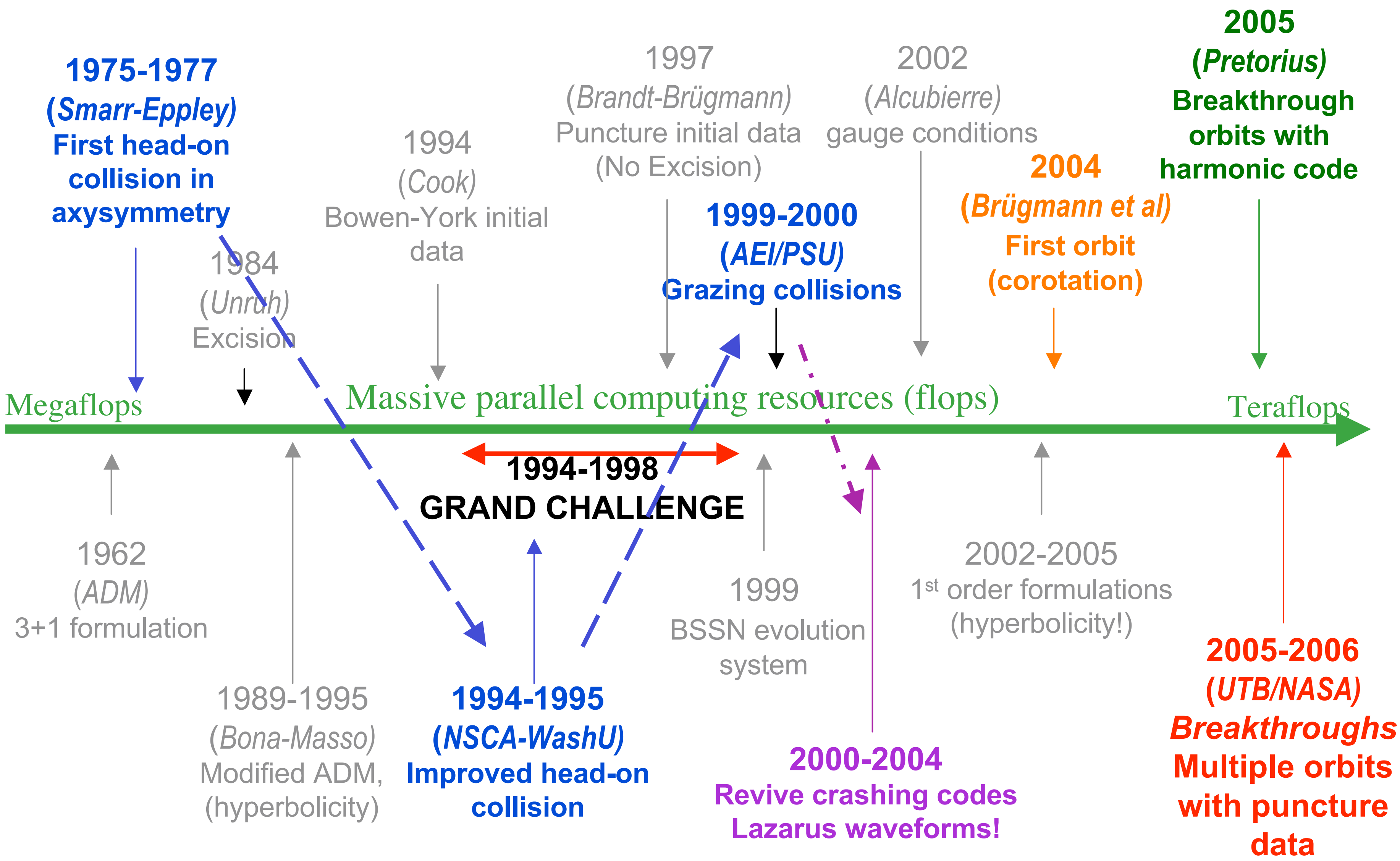

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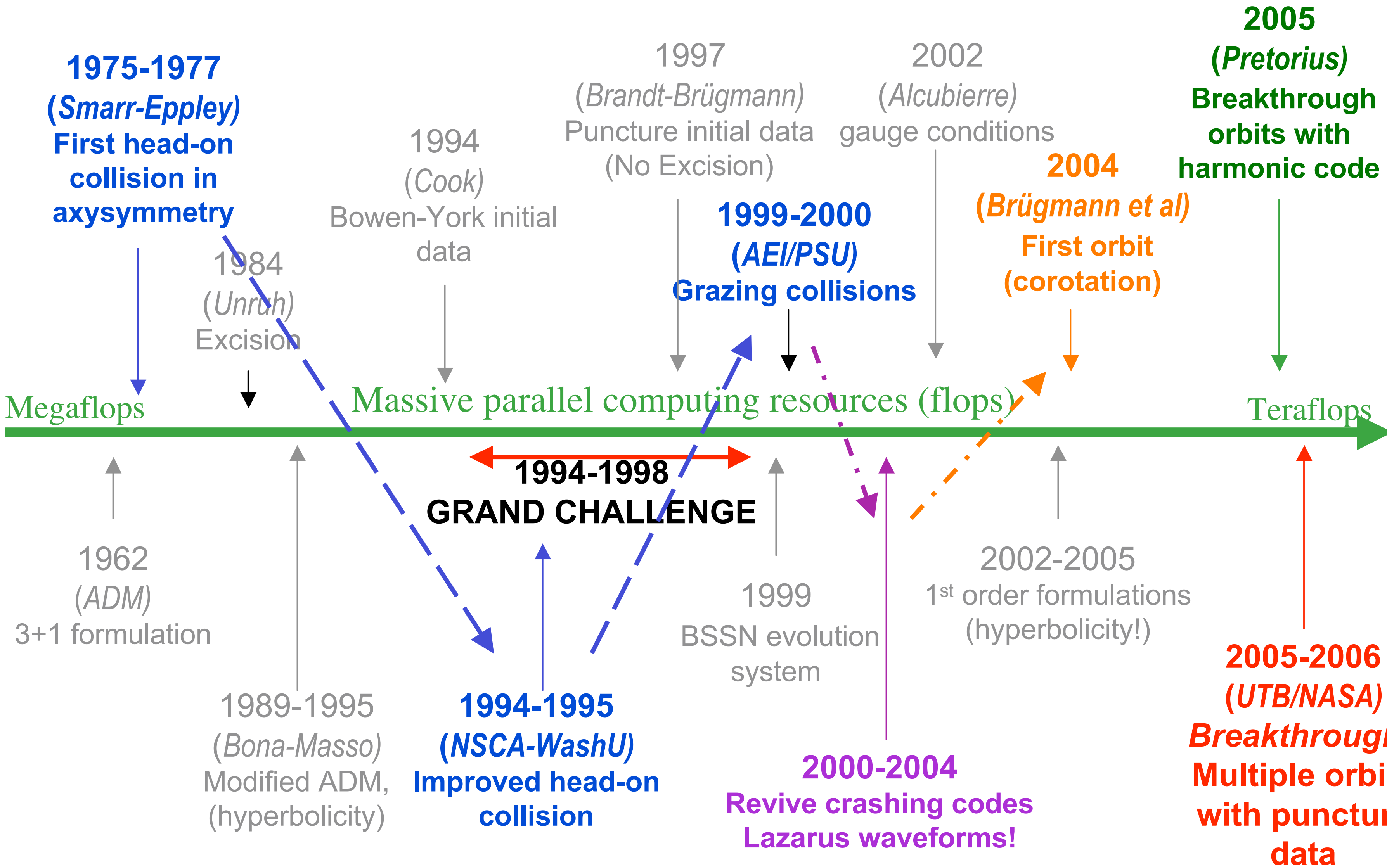

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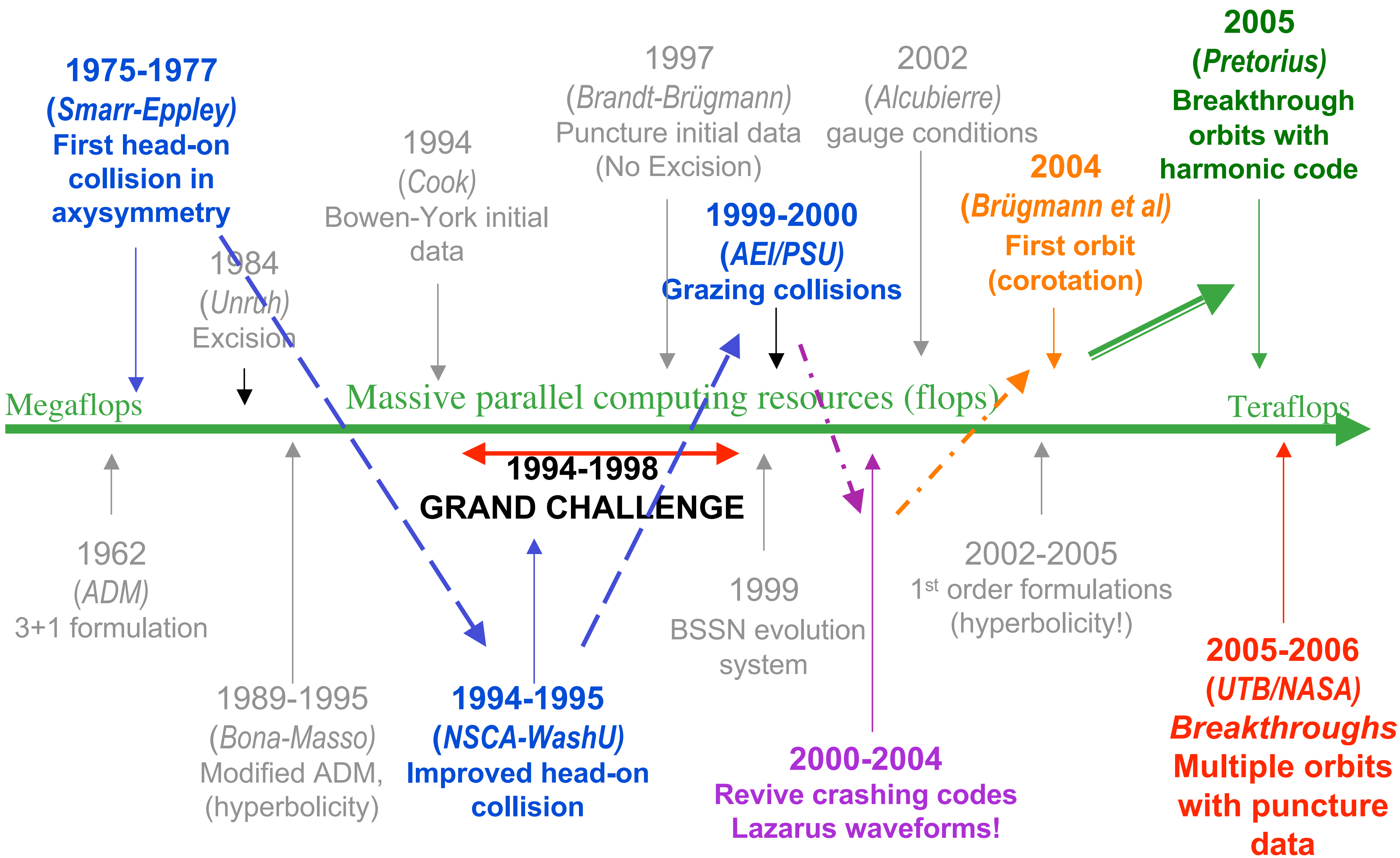

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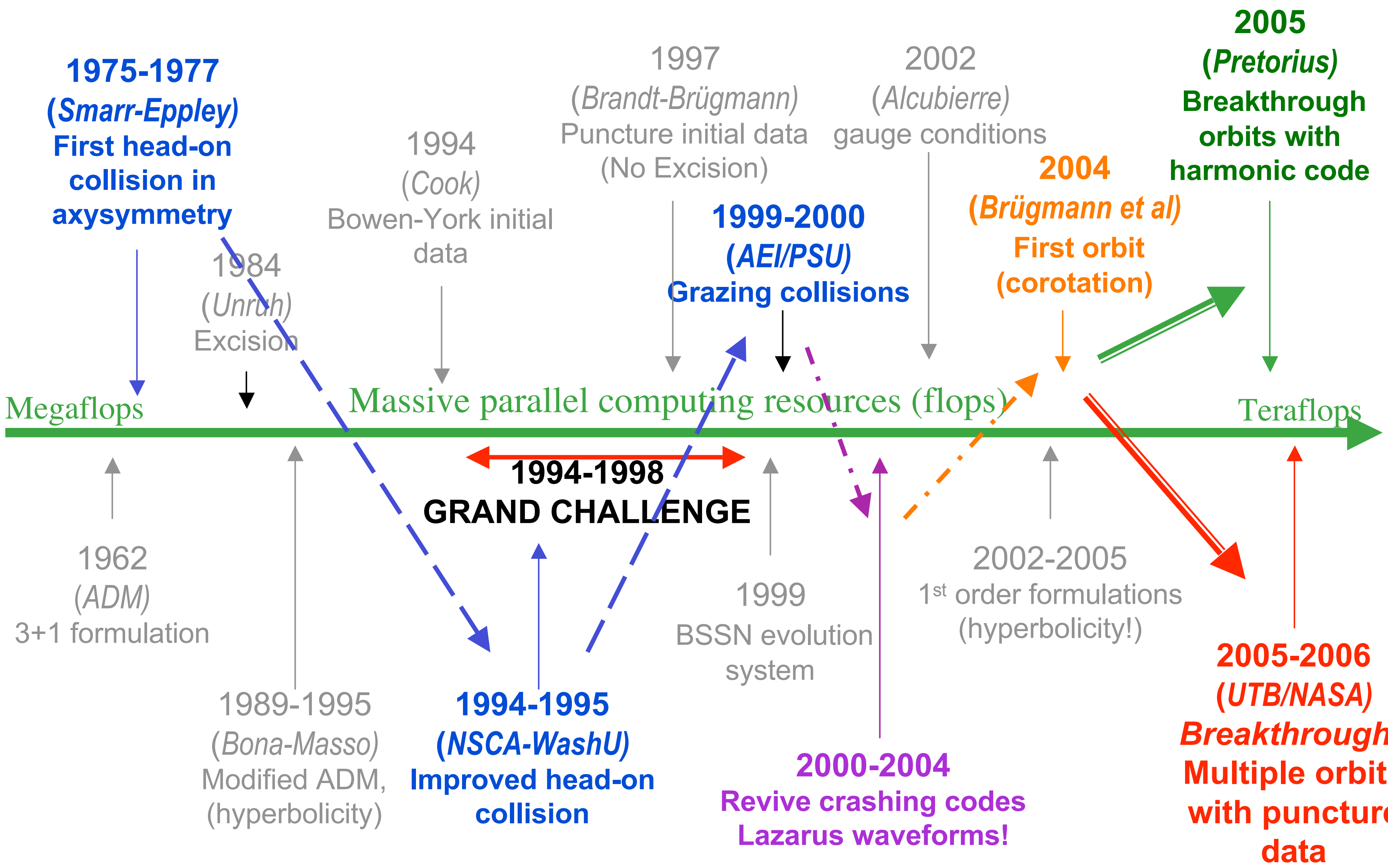

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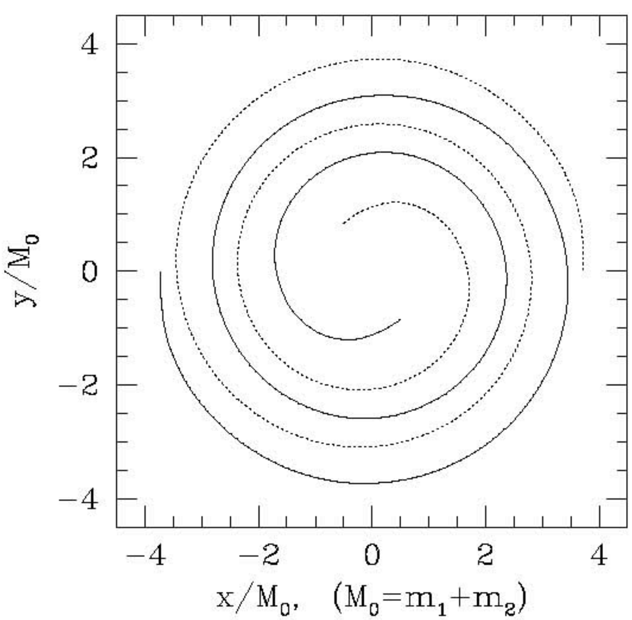
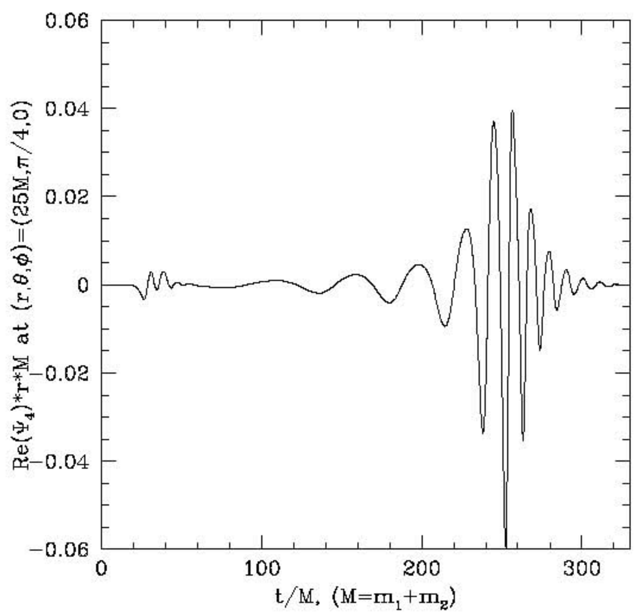
Pretorius breakthrough: different …

In early 2005 Pretorius (Caltech/Alberta, PRL 2005) demonstrates that the binary black hole problem ‘can be done’ in Numerical Relativity (orbits, waveforms etc) but uses a *completely different* system to the standard

- Not 3+1 formalism but evolve directly the 4 metric
- Generalized harmonic coordinates
- Excision, `Constraint damping’, AMR, compactified spatial infinity

but *what are the key ingredients*?

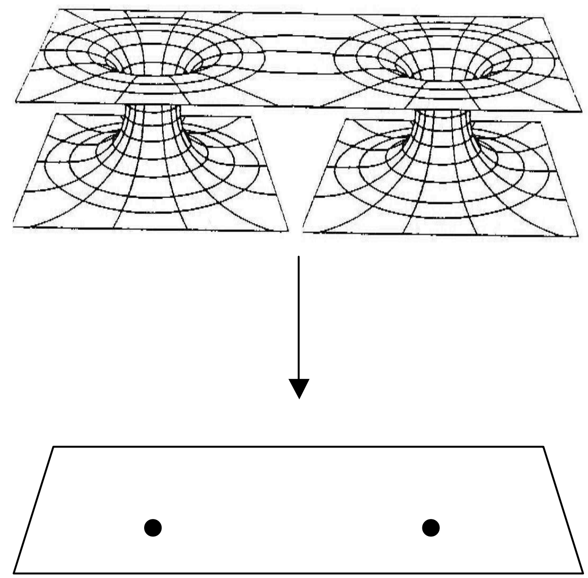




`Moving punctures' breakthrough: standard but simple …

In late 2005, two groups UTB (M.C., C.Lousto, Y. Zlochower, PRL 2006) and NASA Goddard (J.Baker, J.Centrella, D.Choi, M.Koppitz, J.van Meter, PRL 2006) independently achieved multiple orbits and waveforms with a 3+1 approach and rather *standard* techniques but *a key modification*:

- Punctures (no excision)
- Standard BSSN formulation
- 1+log slicing, modified _-driver shifts
- No corotation, *instead allow the punctures to move by absorbing singularities in the BSSN conformal factor _*
  - NASA discretize _ directly …
  - UTB uses non singular _=exp(-4_)
- High-resolution (4th order + AMR or Fisheye).



$$\gamma_{ab} = (\psi_{BL} + u)^4 \delta_{ab}$$

$$\psi_{BL} = 1+\sum_{i=1}^{n} m_i/(2r_i)$$

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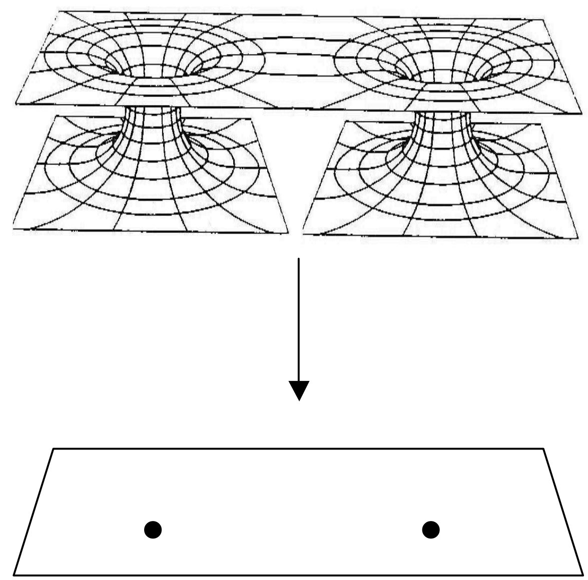
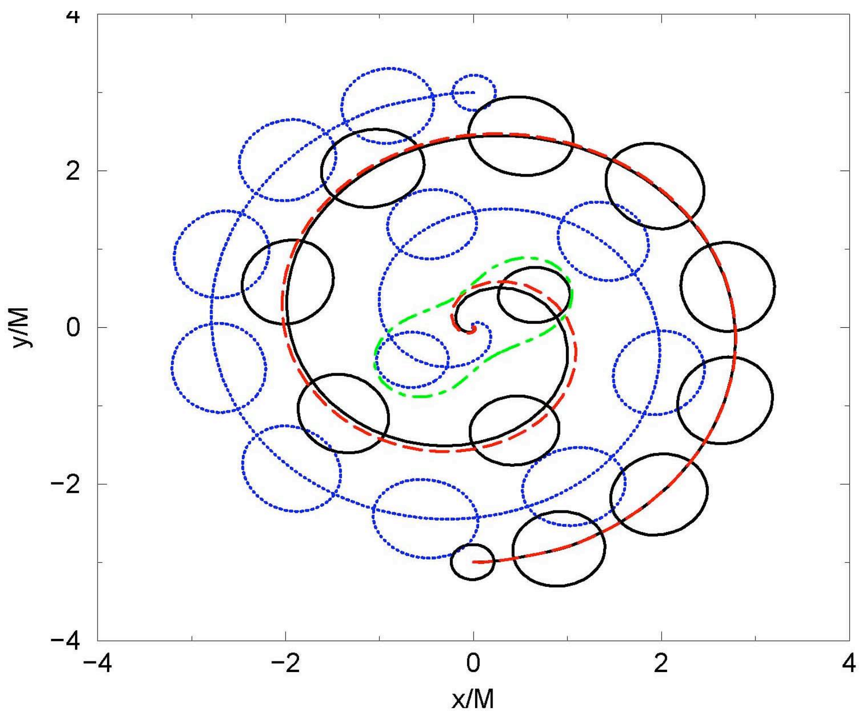


$$\gamma_{ab} = (\psi_{BL} + u)^4 \delta_{ab}$$

$$\psi_{BL} = 1 + \sum_{i=1}^{n} m_i/(2r_i)$$

‘E pur si mouve’ (*Galileo*)

UTB: the last orbit of equal-mass non-spinning binary black holes



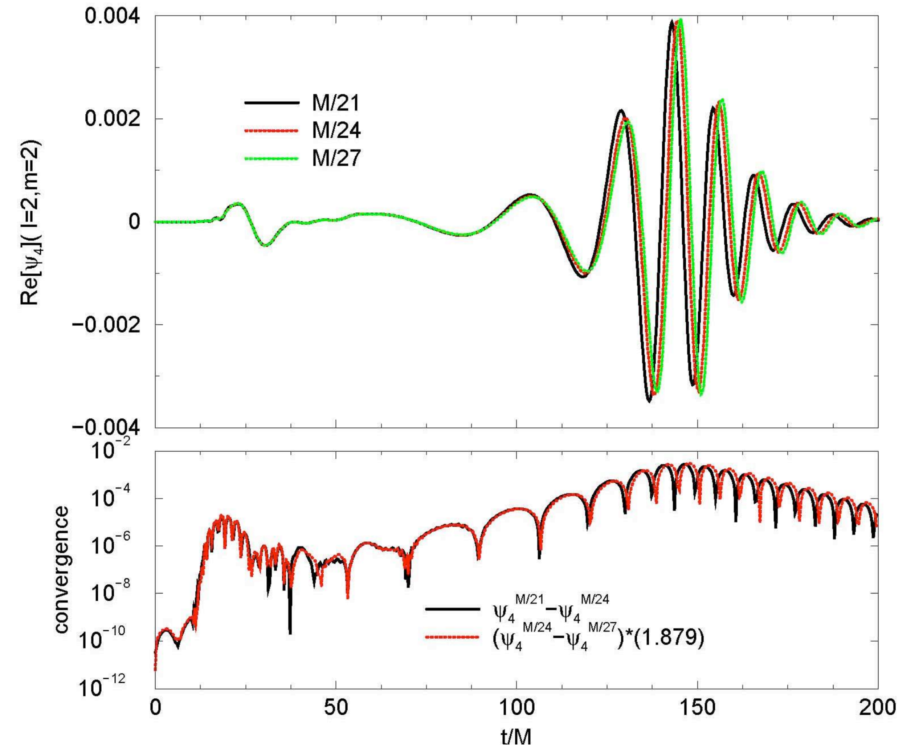
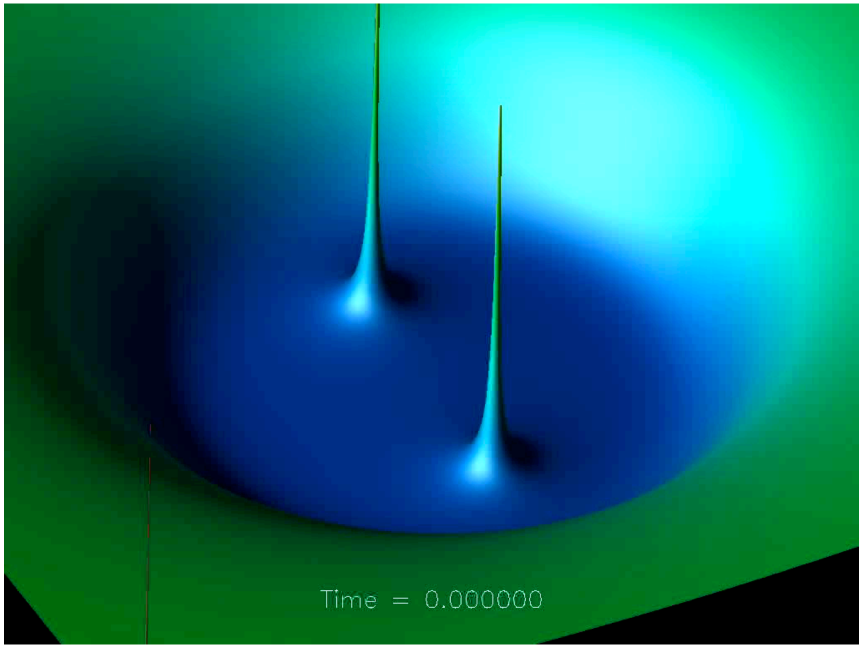


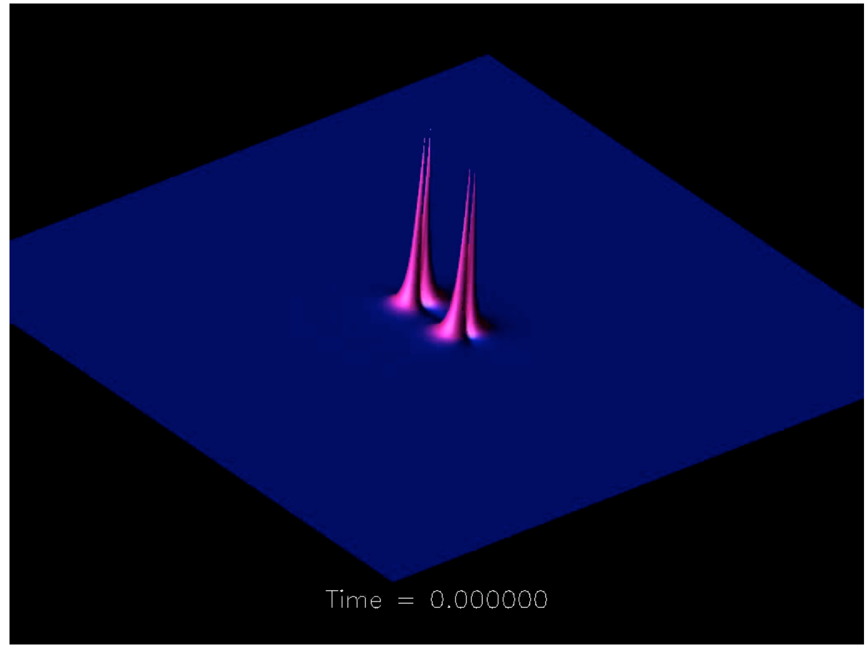
Table 1: Results of the evolution as determined from the waveform and the remnant horizon.

Method	E_{rad}/M_{ADM}	J_{rad}/J_{ADM}	T_{cah}/M	$a/M_{\mathcal{H}}$
Radiation	$(3.18 \pm 0.2)\%$	$(24.3 \pm 2)\%$	≈ 121	0.673 ± 0.002
Horizon	$(3.3 \pm 0.2)\%$	$(24.7 \pm 0.4)\%$	≈ 125	0.688 ± 0.001

M.Campanelli, C.Lousto & Y.Zlochower (UTB), *The last orbit of binary black holes*, Rapid Communication PRD (2006)

UTB: the last orbit of equal-mass non-spinning binary black holes





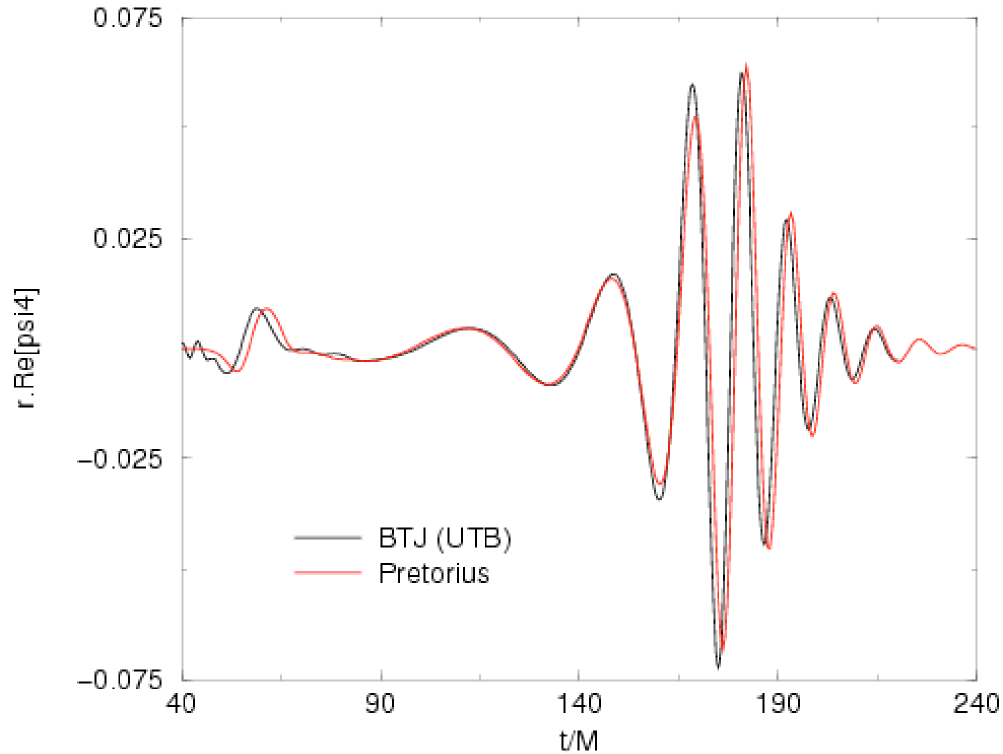
Conformal factor _

_4~d_/dt_[h+ +ihx]

Note that each simulation (equal-mass, non-spinning BBH) takes about 2-4 weeks on a 64 nodes Linux cluster …

M.Campanelli, C.Lousto & Y.Zlochower (UTB), *The last orbit of binary black holes*, Rapid Communication PRD (2006)

Universality of merger waveforms: a first (crude) comparison …



- Different initial data (with same parameters): UTB (puncture initial data) vs. Pretorius (thin-sandwich initial data), different resolutions and evolution systems, but same merger waveforms!? *Work in progress …*

- NASA simulations of multiple orbits of black holes also show that (when shifted in time), the late time behavior is the same for different initial separations (see Centrella's talk this morning)

- Next compare UTB and NASA results …

UTB: Orbital 'hang-up' of spinning black-hole mergers

- Spinning BBH Initial Data:
  - Enforce: ADM mass (M)=1, _M=0.05 (same orbital period 125M)
  - Si/m_= -0.75, 0.0, +0.75 (J/M_>1), other parameters from 3PN

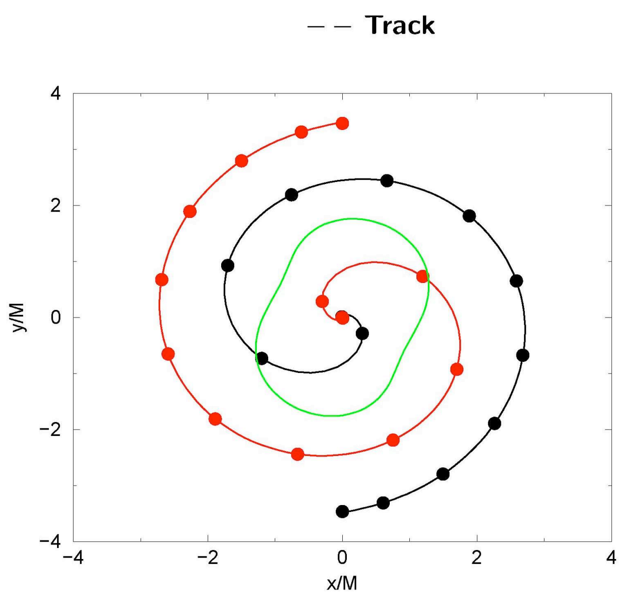


Figure 4: Puncture tracks for the − − configuration.

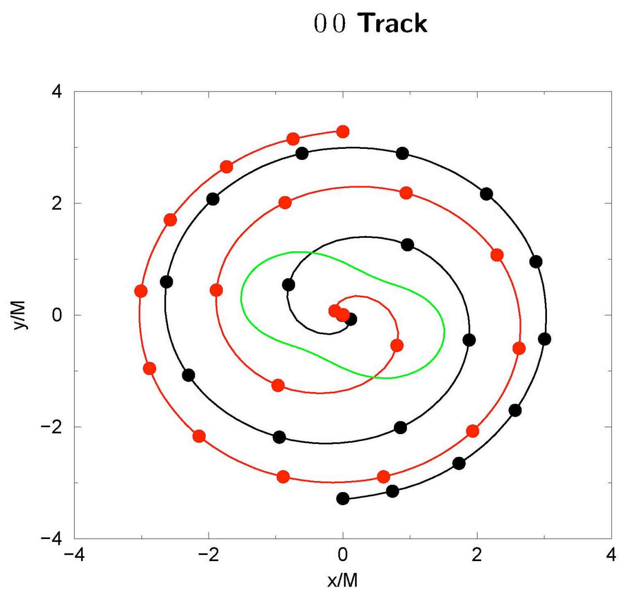


Figure 5: Puncture tracks for the 0 0 configuration.

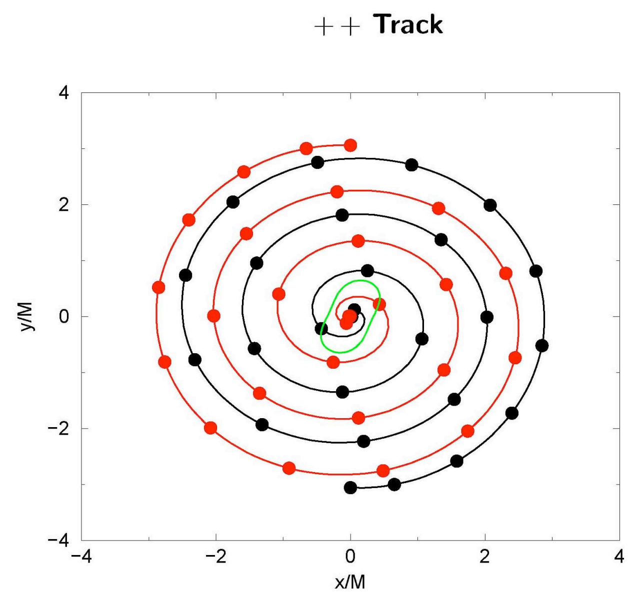


Figure 6: Puncture tracks for the + + configuration.

- Spin-orbit coupling effects:
  - in the (--) case tends to prompt an early merger ~ 1 orbit
  - in the (++) case tends to delay the merger (hang-up) ~ 3 orbits

M.Campanelli, C.Lousto & Y.Zlochower (UTB), *Gravitational radiation from spinning black-hole binaries: The Orbital hang up*, submitted to PRD (2006); gr-qc/0604012

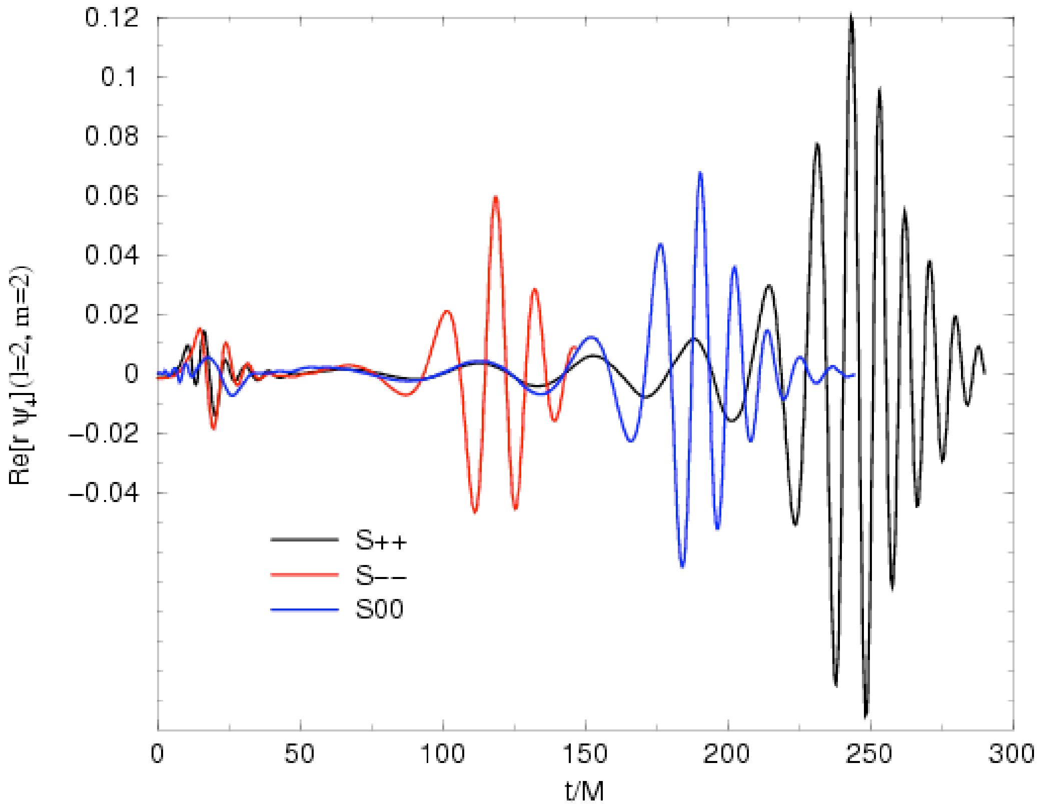


Table 1: Results of the evolution as determined from the waveform and the remnant horizon.

Config	E_{rad}/M_{ADM}	J_{rad}/J_{ADM}	T_{cah}/M	$a/M_{\mathcal{H}}$
$++$	$(6.5 \pm 0.1)\%$	$(33.8 \pm 1.5)\%$	≈ 232	0.892 ± 0.002
$0\,0$	$(3.51 \pm 0.01)\%$	$(26.9 \pm 0.1)\%$	≈ 161	0.688 ± 0.001
$--$	$(2.1 \pm 0.1)\%$	$(26 \pm 2)\%$	≈ 105	0.44 ± 0.01

Extrapolating to maximal individual spins we get $a/M^2 = .976$ (linear) and $a/M^2 = .952$ (quadratic).

Conclusions

- Remarkable progress in 1-2 years:
  - Moving punctures approaches (UTB and NASA) quickly adopted with minor changes by several groups, including PSU, FAU, Jena, CCT/LSU, AEI, and UNAM
  - A variation of the harmonic approach (Pretorius) now adopted by Caltech/Cornell groups (adapted to 1st order formulation, spectral code etc)
- Waveforms for equal-mass non-spinning BBH merger appear to be 'universal'
  - The merger is relatively insensitive to small changes of the initial data parameters!
  - Not true for the orbital dynamics (small ellipticity in all initial data)
- Multiple orbits (tens) are necessary to explore overlapping with PN results
  - Accuracy in the phase important …
  - Work in progress at UTB/FAU to built PN initial data for puncture evolution
- We also started to explore the parameter space:
  - NASA, PSU etc _ unequal-mass BBH mergers
  - UTB etc _ spinning BBH mergers
- Most groups are now limited by:
  - Computational resources …
  - Sophisticated software algorithms to improve accuracy (AMR)
- Numerical relativity is finally entering a golden age of applications!

UTB approach: modified BSSN evolution system

$$
\begin{aligned}
\partial_0 \tilde{\gamma}_{ij} &= -2\alpha \tilde{A}_{ij}, \\
\partial_t \chi &= \frac{2}{3}\chi\left(\alpha K - \partial_a \beta^a\right) + \beta^i \partial_i \chi, \\
\partial_0 \tilde{A}_{ij} &= \chi\left(-D_i D_j \alpha + \alpha R_{ij}\right)^{TF} + \\
& \alpha\left(K \tilde{A}_{ij} - 2\tilde{A}_{ik}\tilde{A}^k_j\right), \\
\partial_0 K &= -D^i D_i \alpha + \alpha\left(\tilde{A}_{ij}\tilde{A}^{ij} + \frac{1}{3}K^2\right), \\
\partial_t \tilde{\Gamma}^i &= \tilde{\gamma}^{jk}\partial_j\partial_k\beta^i + \frac{1}{3}\tilde{\gamma}^{ij}\partial_j\partial_k\beta^k + \beta^j\partial_j\tilde{\Gamma}^i - \\
& \tilde{\Gamma}^j\partial_j\beta^i + \frac{2}{3}\tilde{\Gamma}^i\partial_j\beta^j - 2\tilde{A}^{ij}\partial_j\alpha + \\
& 2\alpha\left(\tilde{\Gamma}^i{}_{jk}\tilde{A}^{jk} + 6\tilde{A}^{ij}\partial_j\phi - \frac{2}{3}\tilde{\gamma}^{ij}\partial_j K\right),
\end{aligned}
$$

Replace ϕ $(O(\log r))$ with $\chi = e^{-4\phi}$ $(O(r^4))$
$\partial_0 \alpha = -2\alpha K$
$\partial_t \beta^a = B^a$, $\partial_t B^a = 3/4\partial_t \tilde{\Gamma}^a - \eta B^a$
$\alpha(t=0) = \psi_{BL}^{-2}$ $\beta^i = B^i = 0.$

$$\partial_0 = \partial_t - \mathcal{L}_\beta, \qquad \tilde{\Gamma}^i = -\partial_j \tilde{\gamma}^{ij}.$$

- M.Campanelli, C.O.Lousto, P.Marronetti & Y.Zlochower, PRL (2006); [arXiv:gr-qc/0511048].

The LazEv Code:

- Modularity _ Cactus-based evolution framework
- Flexibility _ *Mathematica* scripts are used to generate C routines
- 4th order finite differencing with MoL integration
  - Higher e_ective resolution for the same number of grid points.
  - Standard 4th order centered stencils for all derivatives, upwinded 4th order stencils for the advection terms, standard 4th order RK for time evolution
  - No dissipation needed
- Radiative boundary conditions
- Punctures between grid points, pi-symmetry and reflection symmetry
- Unigrid with multi-regional fisheye: *R=Cr*

$$
\begin{aligned}
C &= a_n + \sum_{i=1}^{n} \kappa_i / r \log\left(\frac{\cosh((r + r0_i)/s_i)}{\cosh((r - r0_i)/s_i)}\right), \\
\kappa_i &= \frac{(a_{i-1} - a_i) s_i}{2\, \tanh(r0_i/s_i)},
\end{aligned}
$$

(effective FMR with 3 regions and boundaries up to 200M)

• Y. Zlochower, J. Baker, M.Campanelli, C.Lousto, PRD 72, 024021 (2005) [arXiv:gr-qc/0505055]

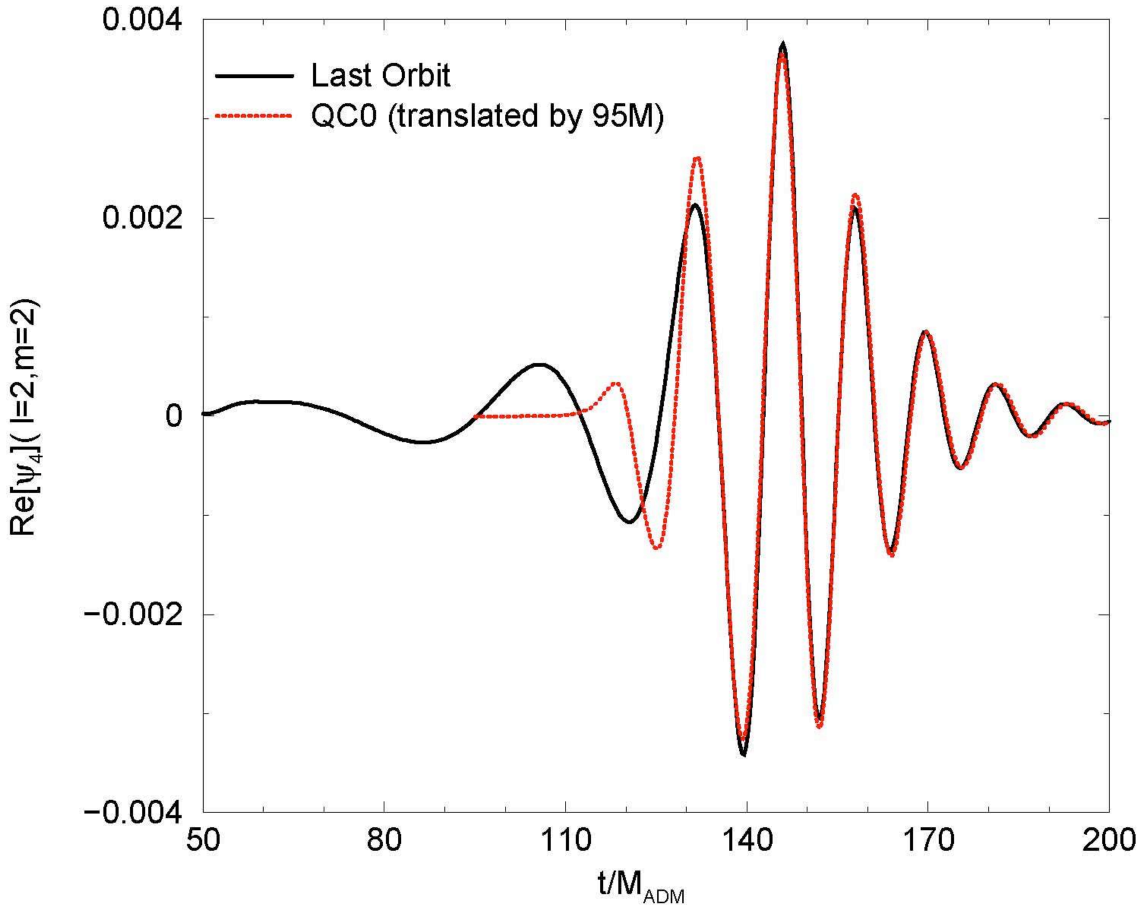


Figure 2: ψ_4 from the 'last orbit' and QC0 ($\Delta t/M = 95$).

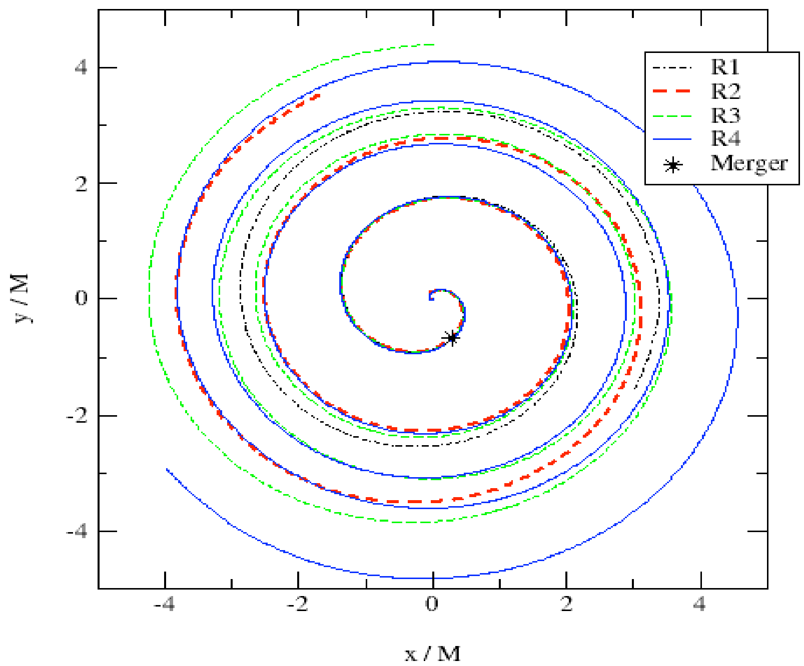
QC0: CAH forms at ~ 20M

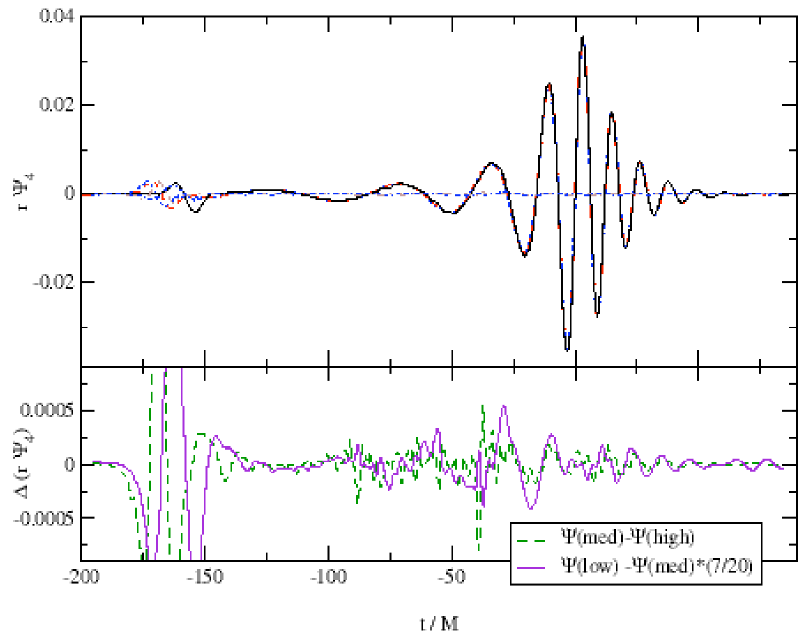
QC5.5: CAH forms at ~115M, extrapolate to 125M

In the waveform the initial spurious gravitational waves are clearly visible

Good agreement with Lazarus waveforms (plunge part)

NASA: multiple orbits from equal-mass non-spinning black hole binaries





NASA simulations showing multiple orbits of black holes. When shifted in time, the late time behavior is the same for different initial separations.

These results confirm the picture of the `universality of the merger waveform'

J.Baker, J.Centrella, D.Choi, M.Koppitz & J.van Meter (NASA), *Binary black hole merger dynamics and waveforms*, PRD (2006) [arXiv:gr-qc/0602026]